

Growth and characterization of ZnTe films grown on GaAs, InAs, GaSb, and ZnTe

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We report the successful growth of ZnTe on nearly lattice-matched III-V buffer layers of InAs (0.75%), GaSb (0.15%), and on GaAs and ZnTe by molecular beam epitaxy. *In situ* reflection high-energy electron diffraction measurements showed the characteristic streak patterns indicative of two-dimensional growth. Photoluminescence measurements on these films show strong and sharp features near the band edge with no detectable luminescence at longer wavelengths. The integrated photoluminescence intensity from the ZnTe layers increased with better lattice match to the buffer layer. The ZnTe epilayers grown on high-purity ZnTe substrates exhibited stronger luminescence than the substrates. We observe narrow luminescence linewidths (full width at half maximum ≈ 1 –2 Å) indicative of uniform high quality growth. Secondary-ion mass spectroscopy and electron microprobe measurements, however, reveal substantial outdiffusion of Ga and In for growths on the III-V buffer layers.

Zinc telluride is a II-VI semiconductor that has a direct band gap in the green region of the spectrum. By virtue of this band gap, ZnTe is a natural candidate for visible semiconductor optoelectronics.^{1–3} The ability to grow high quality epitaxial layers of ZnTe is prerequisite for future optoelectronic devices based on ZnTe. In this letter, we demonstrate that high quality epitaxial layers of ZnTe can be grown on nearly lattice-matched InAs and GaSb buffer layers, poorly lattice-matched GaAs buffer layers, and ZnTe substrates.

Although ZnTe is a potentially useful material for optoelectronic applications, there are substantial difficulties associated with doping this material *n* type; it is only possible to achieve *p*-type ZnTe at useful carrier concentrations by traditional growth/doping methods. The ability to achieve both *n*-type and *p*-type material is important for devices based on efficient minority-carrier injection. Thus, it is quite a challenge to achieve *n*-type doping of ZnTe, and fabricate viable optoelectronic devices based on ZnTe.

One of the main factors that is thought to limit donor incorporation in ZnTe is the presence of acceptor impurities, such as Cu and Li.^{4,5} In molecular beam epitaxy growth (MBE), such extrinsic impurity incorporation can be suppressed by several orders of magnitude by high-purity growth under ultrahigh vacuum (UHV). Thus, MBE growth of ZnTe may offer the possibility of *n*-type doping, in addition to the growth of high-purity material. The MBE techniques also offer the unique capability of growing ZnTe on various III-V buffer layers, and thus, fabricating novel devices with integrated II-VI/III-V heterostructures for future optoelectronics.^{6,7}

We report the growth of ZnTe on nearly lattice-matched InAs and GaSb buffer layers, on GaAs and on ZnTe. We observe strong and sharp luminescence features near the

band edge in these ZnTe films. For the growth of ZnTe on GaAs, in contrast to the previous literature,^{8,9} we report epilayers exhibiting significantly higher energy peaks for similar growth conditions. Our studies indicate that GaSb is the best III-V substrate for the growth of ZnTe epilayers. While our results are in general agreement with the previous studies of ZnTe on ZnTe,¹⁰ in addition we find that high quality epitaxial growth can be achieved on randomly oriented ZnTe substrates, and the presence of the oxygen isoelectronic impurity⁵ can be controlled.

The samples in which ZnTe layers were grown on III-V buffer layers (GaAs, InAs, and GaSb) were transferred through an UHV transfer tube to the II-VI growth chamber (PHI-430) following the growth of the buffer layers in a separate III-V growth chamber. This capability of our MBE system allows us to initiate ZnTe growth on the as-grown III-V buffer layers without any exposure to the atmosphere. In Table I we have cataloged various growth parameters for the samples discussed in this letter. The buffer layers for samples 1, 2, and 3 were prepared by initially growing a 0.5 μm layer of *n*⁺-GaAs on an *n*⁺-GaAs substrate. Subsequently, for the buffer layer of sample 2, a five-period (2 ML/2 ML) GaAs-In_{0.7}Ga_{0.3}As superlattice was grown followed by a 1.5 μm InAs layer, while for the buffer layer of sample 3, a ten-period (1 ML/1 ML) GaAs-GaSb superlattice was grown, followed by a 1.0 μm GaSb layer. The InAs

TABLE I. Growth parameters of the samples.

Sample No.	Buffer layer	Zn:Te flux ratio	Lattice mismatch	ZnTe layer thicknesses
1	GaAs	2:1	7.30%	2.4 μm
2	InAs	2:1	0.75%	2.6 μm
3	GaSb	2:1	0.15%	2.6 μm
4	ZnTe	1:1	0.00%	2.2 μm

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buffer layer of sample 2 was n^{-1} doped, while the GaSb buffer layer of sample 3 was nominally undoped. For samples 1, 2, and 3, a 2.2–2.6 μm ZnTe layer was grown with a ZnTe source and an extra Zn flux. This extra Zn flux was turned on to achieve a Zn-rich growth surface which is desirable for the growth of good quality epitaxial layers.^{8,9} For the growths of samples 1–3, the flux ratio of Zn:Te was monitored to be 2:1, and the growth temperature was set at 330 °C.

For the growth of ZnTe on ZnTe, due to the limited availability of ZnTe substrates, growth was done on small (1 cm^2) pieces of ZnTe held by Si springs. Typical substrates were oriented in random directions. A conventional method of indium bonding to hold the ZnTe substrates was not satisfactory since we found that indium creeps to the top surface of these small samples interfering with growth.

The growth of II-VI epilayers was monitored by *in situ* reflection high-energy electron diffraction (RHEED). In Fig. 1(a), we show the representative RHEED pattern for the growth of ZnTe on GaSb buffer layers. The streaky pattern shown in this figure is indicative of two-dimensional growth. For the growth of ZnTe on GaSb, with only a ZnTe flux present, we observe a (2×1) reconstruction pattern as shown in Fig. 1(a), corresponding to a Te-rich growth surface. However, for a Zn:Te flux ratio of 2:1, we observe that the inbetween dimmer lines on Fig. 1(a) decrease in intensity corresponding to a Zn-rich growth surface. These results are analogous to those obtained in previous work on the growth of ZnTe on GaAs.^{8,9} The characteristic RHEED pattern for the growth of ZnTe on a randomly oriented ZnTe

substrate with a Zn:Te ratio of 1:1 is shown in Fig. 1(b). This RHEED pattern is also indicative of two-dimensional growth.

The surfaces of the epilayers were characterized by optical microscopy and scanning electron microscopy (SEM). The epilayer surfaces appeared to be smooth and featureless for the growth conditions reported above.

The photoluminescence spectra for the samples were obtained for temperatures between 5 and 100 K. We used 1.0 mW of the 4880 Å line of an argon ion laser for above band-gap pumping. The photoluminescence was detected in the energy range from 1.4 to 2.4 eV.

Photoluminescence from sample 1 (ZnTe on GaAs) at 5 K is shown in Fig. 2. The sample photoluminescence is dominated by significantly higher energy features associated with bound exciton emission than previously reported growths on GaAs.^{8,9} We also have much narrower linewidths [full width at half maximum (FWHM) $\approx 1\text{--}2$ Å] than earlier reported work, indicating uniform and higher quality growth. There is no detectable luminescence from donor-acceptor pairs or deep centers. However, total luminescence intensity of the epilayers grown on GaAs is significantly weaker than for high-purity bulk ZnTe for identical pump conditions. The photoluminescence peaks are coincident with the bulk values reported in the earlier literature,^{1–5} indicating no observable strain shifts in these thick epitaxial layers. Although there is a large lattice mismatch for ZnTe on GaAs, we find that strain-relaxed high-purity epitaxial layers of ZnTe can be grown if the epilayers are grown thicker than about 0.5 μm . However, we were able to achieve high quality luminescence from ZnTe epilayers grown on GaAs buffer layers, when the ZnTe layer thickness was less than 0.5 μm .

Photoluminescence from samples grown on nearly lattice-matched III-V buffer layers (InAs and GaSb) are shown in Figs. 3(a) and 3(b). We find a significant improvement in the integrated photoluminescence intensity as the lattice mismatch is decreased; the luminescence from sample 2 (InAs buffer) is stronger than in sample 1 (GaAs buffer),

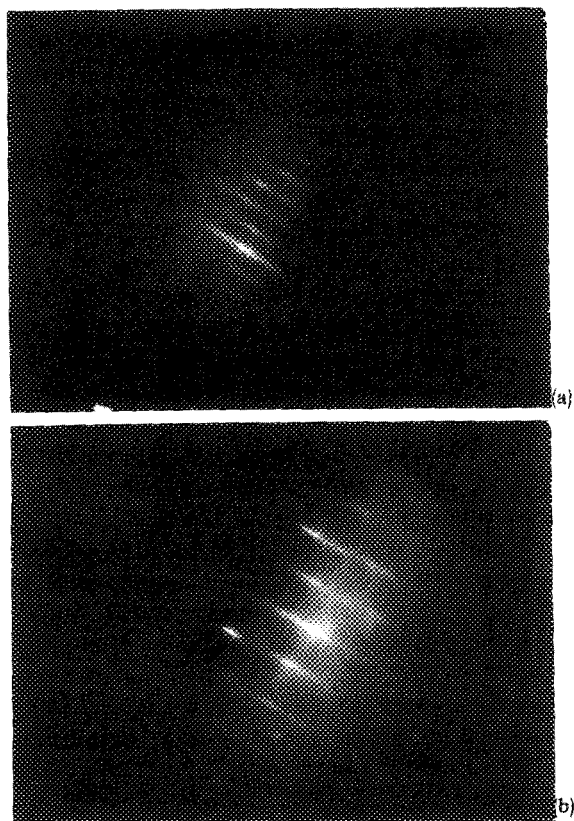


FIG. 1. RHEED patterns for (a) growth of ZnTe on GaSb and (b) growth of ZnTe on ZnTe. These patterns indicate two-dimensional growth. The RHEED pattern of (a) is referred to a $\{011\}$ axis, while the axis for pattern (b) is not known since the substrate was randomly oriented. The growth temperature was 330 °C for both of these samples.

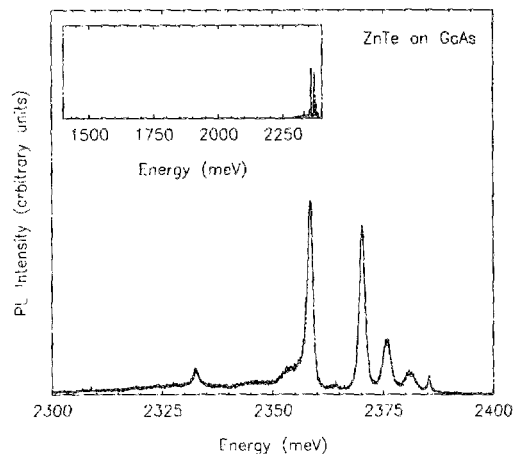


FIG. 2. Photoluminescence (PL) from ZnTe epilayers grown on GaAs. The dominant features are due to bound excitons. These samples exhibit PL at a higher energy than previous work (see Refs. 8 and 9) by others. We have also shown the PL spectrum over a wide range of energy (1.4–2.4 eV) in the smaller window. Note the absence of donor-acceptor and deep-center luminescence.

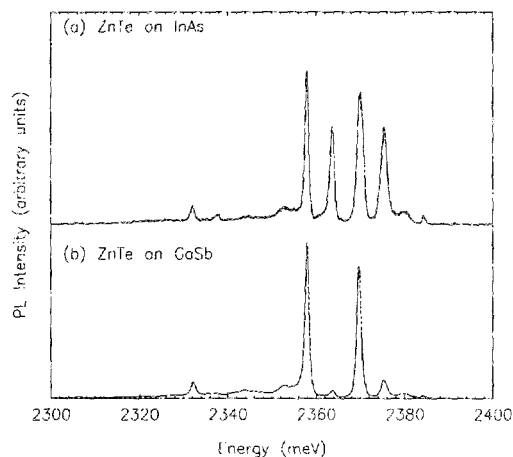


FIG. 3. PL from ZnTe grown on InAs and GaSb buffer layers. The PL features are similar to Fig. 2. We have identified an In-related line at 2.364 eV. (a) and (b) were normalized for the maximum intensity line to have the same height. Note the absence of donor-acceptor and deep-center luminescence.

but weaker than in sample 3 (GaSb buffer). The luminescence from sample 3 is comparable in intensity with the high-purity bulk ZnTe substrates. As with Fig. 2, in Figs. 3(a) and 3(b), there is no detectable luminescence from donor-acceptor pairs or deep centers.

The photoluminescence from sample 4 (growth on ZnTe substrate) at 5 K is shown in Fig. 4(a), while the substrate luminescence is shown in Fig. 4(b). We find that the luminescence of the epilayers on ZnTe substrates is stronger than from the substrates. These epilayers also show no detectable luminescence from donor-acceptor pairs or deep centers.

From our luminescence spectra we have identified an In-related bound exciton line based upon its appearance and disappearance when In is present or absent in the buffer layer. This line occurs at 2.364 eV. We have also observed the bound exciton luminescence associated with cation vacancies (V_{Zn}) at 2.369 eV.¹¹⁻¹³ The luminescence peak at 2.375 eV commonly observed in bulk ZnTe has been attributed to a variety of acceptor species including Cu, Li, As, and P.¹⁻⁵ The other sharp peak we observe in these spectra occurs at 2.358 eV. In contrast to the photoluminescence spectra from the samples grown on III-V buffer layers that exhibit several sharp peaks, the epilayers grown on ZnTe show only a single characteristic peak close to 2.375 eV, as shown in Fig. 4(a).

We have also performed electron microprobe analysis (EMA) and depth resolving secondary-ion mass spectroscopy (SIMS) analysis on our samples. The EMA results for ZnTe on GaAs and ZnTe on InAs show substantial outdiffusion of the Ga and In cations. The SIMS profile and the EMA indicate that the surface of the ZnTe layer has a higher concentration of Ga and In than in the ZnTe epilayer. These results are in agreement with the photoluminescence characterization. We also find that there is no significant back diffusion of Te into the III-V buffer layers.

We have reported the successful growth of ZnTe epilayers on GaAs, InAs, GaSb, and ZnTe. We observe sharp, strong near-band-edge luminescence from these samples indicating high quality material. Our growth on GaAs shows

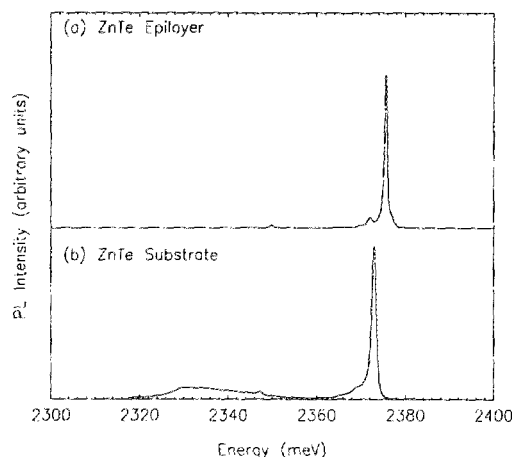


FIG. 4. PL from ZnTe grown on ZnTe substrates. The PL from the epilayer shows a single sharp line at 2.375 eV. (a) and (b) were normalized for the maximum intensity line to have the same height. Note the absence of the donor-acceptor pair luminescence from the epilayer compared to the substrate. The substrate peaks in (b) are about 3 meV lower than in the epilayer probably due to the very different growth conditions under which they were grown.

higher energy luminescence than previous work. The total luminescence increases with better lattice-matched growth. Based on our results, we suggest that GaSb is the best III-V buffer layer for the MBE growth of ZnTe. However, growth of ZnTe on ZnTe yields superior material (characterized by the highest integrated photoluminescence) to any of the growths on III-V buffer layers, or the high-purity ZnTe substrate. We also find substantial outdiffusion of Ga and In cations from the buffer layers. The observation of strong, near-band-edge luminescence from ZnTe is encouraging in the search for visible light emitters based on ZnTe.

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